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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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MILLSTONE SIGNAL PROCESSING

R. A. FORD
Group 91

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PROJECT REPORT STK-104

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ABSTRACT

This report describes the new signal processing portions of the Millstone radar. Included is the waveform design for deep space search and tracking functions and the implementation and integration of these functions into the existing radar. A computer controlled digital waveform generator and a programmable array processor are the two important pieces of hardware required in the upgrade.

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FOREWORD

This report is one of a series prepared under the Satellite Tracking Program. The series reports on a variety of subjects, including: deep space satellite tracking operations and system improvement at the Millstone Hill Radar; results of satellite data analysis; theoretical analyses of radar signal and signature processing; and system planning and concept studies.

The effort covered in this report was sponsored by the Aerospace Defense Command (ADCOM) of the United States Air Force.

I. INTRODUCTION

This report describes the upgrade of the signal processing portions of the Millstone L-band radar which is currently used for the tracking of deep space objects. This upgrade will enhance its capability in two important areas: increased range and doppler coverage during the search mode, and increased bandwidth during the track mode. This will be accomplished with the introduction of two new pieces of equipment. One is a computer controlled waveform generator which will produce CW or chirp pulses of any duration or bandwidth within the capabilities of the transmitter. The other is a programmable signal processor which is capable of processing, in real time, each of the different waveforms that will be associated with the different modes of operation of the radar. The feasibility of using different waveforms, each more ideally suited to the specific search or track task, is one of the major benefits of the programmable signal processor. Without this piece of equipment, a substantial variety of additional hardware would be required for this type of signal processing. The immediate benefits of this modification to Millstone will be an increase in the doppler search window by about a factor of 8 and an increase in the bandwidth of the tracking waveform by about a factor of 75.

II. LOW ALTITUDE SEARCH

During low altitude search, the signal to noise ratio is high enough to preclude the need for large amounts of coherent integration. The implication

here is that the signal processor will not be memory limited and hence the waveform and processing may be selected with a relatively large number of resolution cells which will be restricted only by the constraints of processing the waveform in real time. Another constraint is a reasonably small number of IF filters, tentatively only 8 KHz and 100 KHz. Based on this, a chirp pulse of 80 KHz bandwidth with one to two milliseconds duration at a PRF of 20 to 30 Hz is selected. Each succeeding pulse will have the alternate slope, either up or down. This up-down chirp waveform will enable measurements of range and range rate from each pair of pulses by making use of the range doppler coupling that is inherent in chirp signals.

That is, for an up chirp waveform

$$R_{meas} = R_{true} + \dot{R}\frac{fo}{k}$$

and for a down chirp

$$R_{meas} = R_{true} - \dot{R}\frac{fo}{k}$$

where

$k = B/T =$ slope of chirp signal

$fo =$ carrier frequency.

The range rate and true range are determined in the following manner. Let the first pulse of the pair be an up chirp. Then the measured range is

$$R_1 = R_t + \dot{R}\frac{fo}{k}$$

where R_t is the true range at the time that the energy from this pulse was

on the target. One PRI later the true range is

$$R_t + \dot{R}\ PRI$$

and the pulse is a down chirp so the measured range is

$$R_2 = R_t + \dot{R}\ PRI - \dot{R}\,\frac{fo}{k}$$

The difference is

$$R_2 - R_1 = \dot{R}\ PRI - 2\dot{R}\,\frac{fo}{k}$$

and the estimated range rate is

$$\hat{\dot{R}} = \frac{R_2 - R_1}{PRI - 2\,\frac{fo}{k}}\ .$$

The true range estimate which is valid at a time exactly halfway between when the two measurements were made is

$$\hat{R} = \frac{R_1 + R_2}{2}$$

where the time of validity is

$$TT + \frac{PRI}{2} + \hat{R}/c + \frac{\text{pulse length}}{2}$$

and where TT is the time of the start of the first pulse.

With the approximation 2 fo/k >> PRI, the measurement accuracy is

$$\sigma_{\dot{R}} = \frac{\sigma_R\ \sqrt{2}}{2\ fo/k}$$

For small values of slope, this equation is no longer valid, the limit being proportional to wavelength/(2T). This could be seen more clearly from an

ambiguity diagram. In any event, the use of the up-down chirp waveform will yield a range rate accuracy within a factor of two of that which would have been obtained with a CW pulse before interpolation while the range resolution will be improved by approximately a factor of 100.

The size of the range window will be based entirely on the amount of time required to process this waveform and the selected radar PRF. Preliminary estimates indicate that at least a 400 km window will be available and under certain circumstances 1000 km could be obtained, either of which is entirely adequate for short range targets. With this waveform, the target's allowable doppler error is determined by the acceptable doppler mismatch loss in the processing, but certainly 8 KHz would be a reasonable figure. This is a factor of 8 better than the current Millstone Radar.

The processing for this waveform will be correlation processing performed in the frequency domain by computing the Fourier transform of the sampled range window, multiplying by the complex conjugate of the desired signal, then followed by an inverse transform. Currently, it is planned that only noncoherent integration will be permitted. This waveform is not intended for deep space search. Pulse compression of the angle channels will be identical to that of the sum channel, followed by the monopulse computation:

$$\text{angle error} = \text{real part of } \left(\frac{\Delta}{\Sigma}\right).$$

The angle errors will either be noncoherently averaged in the signal processor or they will be saved and the pulse by pulse angle errors of the

target will be transferred to the Harris at the end of the noncoherent integration interval. This will be determined at later date. The preliminary timing estimates for this waveform using a 512 point FFT are shown in Table I. This translates to about a 400 km window. If a larger range window were needed, the FFT size could be doubled, resulting in a 1000 km window. But only a small percentage (1/4 or 1/8) would receive monopulse processing, so that the target would have to be centered in the range window before the angle monopulse data would be available. This, in fact, is a very attractive alternative because of its essentially higher efficiency.

III. DEEP SPACE SEARCH

The long range search waveform is a CW pulse of approximately 1 millisecond duration. The maximum doppler uncertainty is set by the narrow IF filter, about 8 KHz. Range gating and doppler filtering take place in the signal processor. The range gate spacing is determined directly from sensitivity considerations and indirectly by the constraint of not overloading the processor. The average range processing loss is given by

$$20 \log (1 - x/4)$$

in db where x is the range gate spacing in units of the pulse length. Table II illustrates the critical nature of this parameter to the loss budget.

The processing loss with the FFT is a function of the number of zeros which are used for padding as this directly affects the spacing of the filters. Figure 1 shows this loss as a function of the percentage of zeros that are used for padding. It is applicable to both intrapulse and interpulse processing.

TABLE I

TIMING ESTIMATES FOR LOW ATITUDE SEARCH WAVEFORMS

	Sampling rate		100 KHz	
	Window		4 msec	
	Total words		3200 (4 channels)	
DMA interference				1.3 msec
D.C. offset removal				1.3
Sum channel				
	Pulse compression		5.3	
	512 point FFT	2.4		
	Complex multiply	0.5		
	FFT^{-1}	2.4		
	Magnitude		0.35	
	Noncoherent integration		0.4	
	Threshold		0.15	
Total sum channel processing				6.2
Angle channels (each)				
	Pulse compression		5.3	
	Monopulse		2.0	
	Integration		0.4	
Total angle channel processing				15.4
Overhead				3.4
Host interrupt handling				0.2
Total processing				28 msec
PRF: 20-30 Hz				

TABLE II

RANGE PROCESSING LOSS

X	Loss, dB	Relative Processing Load
1/2	1.2	1
1/4	0.6	2
1/8	0.3	4

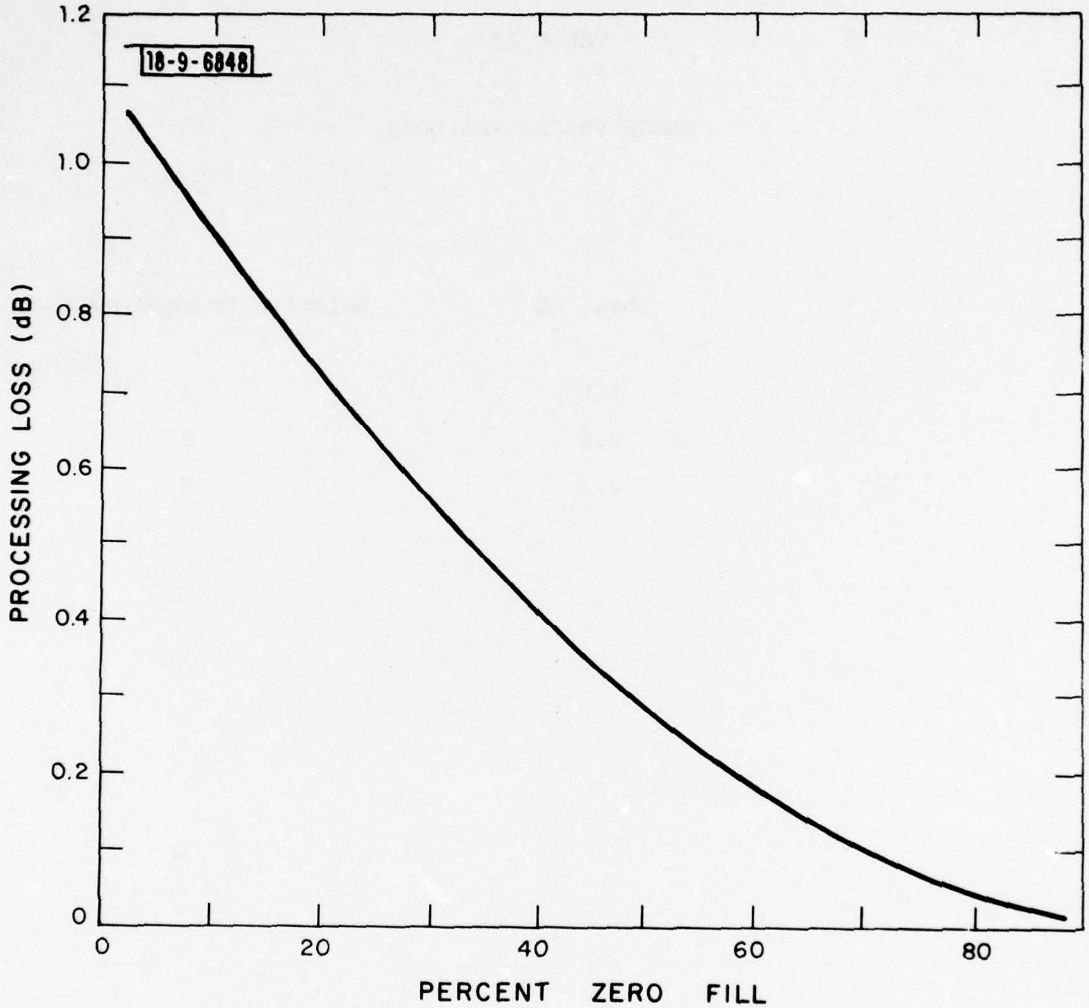

Fig. 1. Doppler quantization loss.

The single pulse matched filtering, or intrapulse processing, may be performed on the fly, i.e., within the next PRI interval after receipt or the raw input data may be saved until all the input data for a coherent integration interval has been received. This option is necessary due to the limited amount of memory available to the signal processor. Because of the overlapped range and doppler samples, a considerable expansion of the amount of data takes place unless only a fairly small subset of the doppler window is retained. The amount of overlap of the range and doppler samples as well as the number of range and doppler samples are all parameters that may be varied as required.

The pulse to pulse coherent processing is performed by the interpulse FFT with weighting and zero-padding available if desired. The maximum number of pulses that may be coherently integrated is 4096 corresponding to about 120 seconds. In addition to this processing, further noncoherent integration may be obtained as desired with a total practical upper limit, based on the capabilities of the signal processor, of about 20 minutes. In addition to the normal pulse to pulse coherent processing available in this mode, the entire range doppler window will always be noncoherently integrated on a pulse to pulse basis. Although not as efficient as coherent integration, the ease with which it may be implemented makes this additional mode very valuable in the search for tumbling targets.

Logic will be incorporated into the signal processor software for the detection of multiple targets. This is expected to be of value for payload-

rocket body combinations which remain within the beamwidth of the radar.

IV. TRACKING MODE

The low ($\approx$80 KHz) and high ($\approx$1 MHz) bandwidth chirp signals will be processed differently in the receiver. The former is used for acquisition where a large range window is required relative to the pulse length, while the latter is only used for tracking where a range window that is a very small percentage of the pulse length is adequate. In this latter case, the most efficient utilization of the digital processor is to compress the pulse in the frequency domain as shown in the diagram of Figure 2. Here, the received signal is mixed, in the correlation mixer, with a replica of the transmitted waveform. The difference frequency is a pulse whose length is the same as that which was originally transmitted but whose frequency is a constant proportional to the range to the target, i.e.,

$$\text{output frequency} = \frac{B}{T}\ \text{(time delay to target)}$$

The use of the 100 KHz IF bandwidth will set the range window to about 15 km or 100 resolution cells. With this method of processing, there is no requirement for 1 MHz A/D converters. The chirp generator will be used then, not only in the exciter to generate the transmitted signal, but also in the receiver to modulate the local oscillator during reception of the high bandwidth chirp signal.

One problem that this mode of processing introduces is a 20 db enhancement of the d.c. offset in the A/D converters on a single pulse basis. This comes about because the output of the I.F. is mixed down to baseband forming

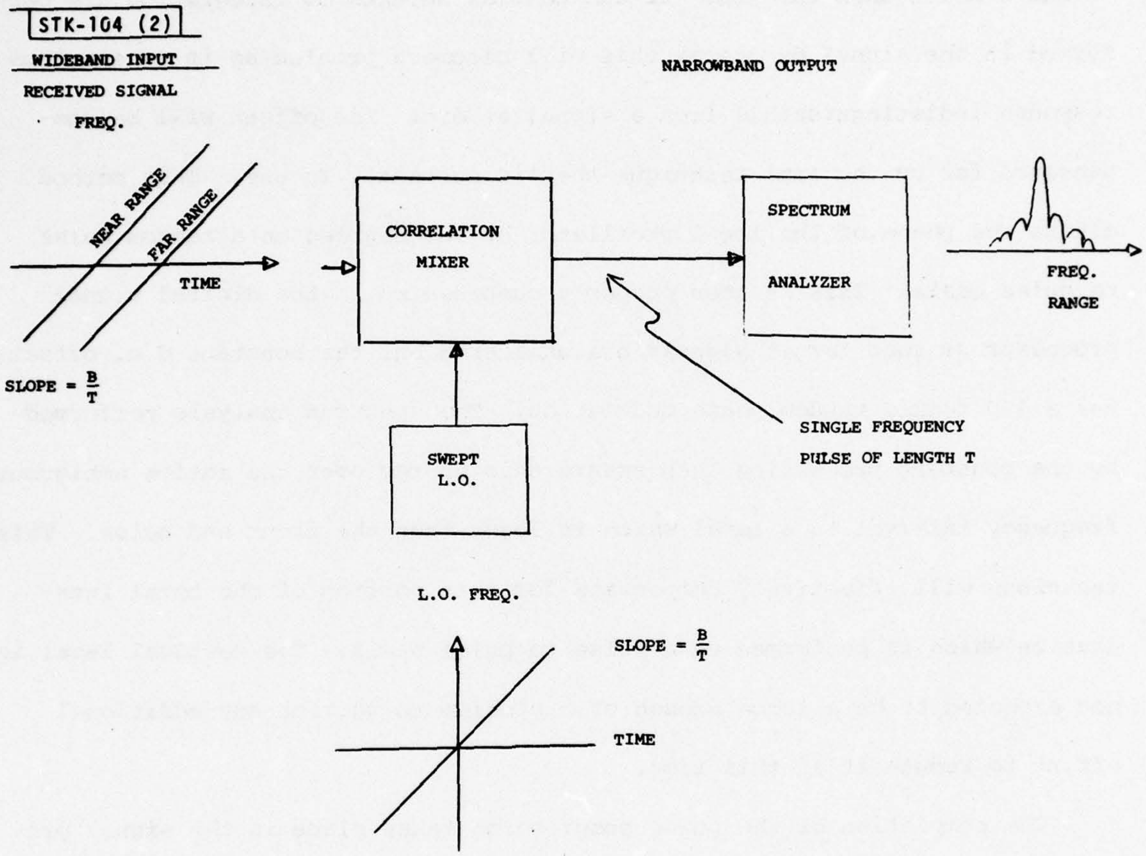

Fig. 2. Method of wideband pulse compression.

the inphase and quadrature video channels which then goes to the A/D converters. Each A/D will normally have a d.c. offset voltage associated with it but smaller than the LSB. If substantial amounts of integration are performed in the signal processor this will become a problem as it is spurious response indistinguishable from a signal at d.c. The offset will be compensated for by the same technique that is currently in use. This method alters the phase of the local oscillator by 180 degrees on a random pulse to pulse basis. This is then properly compensated in the digital signal processor so that target signals are unaltered but the constant d.c. offset has a 180 degree random phase modulation. The spectrum analysis performed by the coherent processing then smears this energy over the entire ambiguous frequency interval to a level which is lower than the front end noise. This technique will effectively compensate for that portion of the total integration which is performed on a pulse to pulse basis. The residual level is not expected to be a large enough of a problem to warrant any additional effort to reduce it at this time.

The completion of the pulse compression takes place in the signal processor where a spectrum analysis is performed by a Fast Fourier Transform algorithm. Weighting and zero padding are used as required for sidelobe suppression and interpolation of the sampled range signal. Variable amounts of coherent and noncoherent pulse to pulse integration will be available with the FFT algorithm being used for the coherent portion.

V. DIGITAL WAVEFORM GENERATOR

The signal source is a digitally generated chirp waveform whose slope and time duration may be selected on a pulse to pulse basis by the radar computer over the range of values which is permitted by the transmitter. The versatility of the digital chirp generator tends to maximize the usefulness of the signal processor by enabling a selection of pulse duration, bandwidth, and processing techniques which are within the capabilities of the processor and which are well suited to the search and tracking requirements of the radar. The chirp generator is based on a design originally intended for the Firepond laser radar. A block diagram is shown in Figure 3. The digital section consists of two accumulators which will generate a signal proportional to t^2. This digital word is used as the address to a pair of read only memories to produce sine (t^2) and cosine (t^2). The D/A converters then produce inphase and quadrature analog video which is applied to a single sideband mixer yielding the final chirp signal which is sent to the exciter. The computer supplies the waveform parameters such as time duration and slope. The start trigger is supplied by the hardware. Any convenient carrier may be selected with the appropriate choice of filters and the carrier phase shifter. The digital logic uses ECL integrated circuits operating at a clock frequency of 50 MHz and hence the need for the 50 MHz sine wave which must be locked to the site standard as shown in the block diagram.

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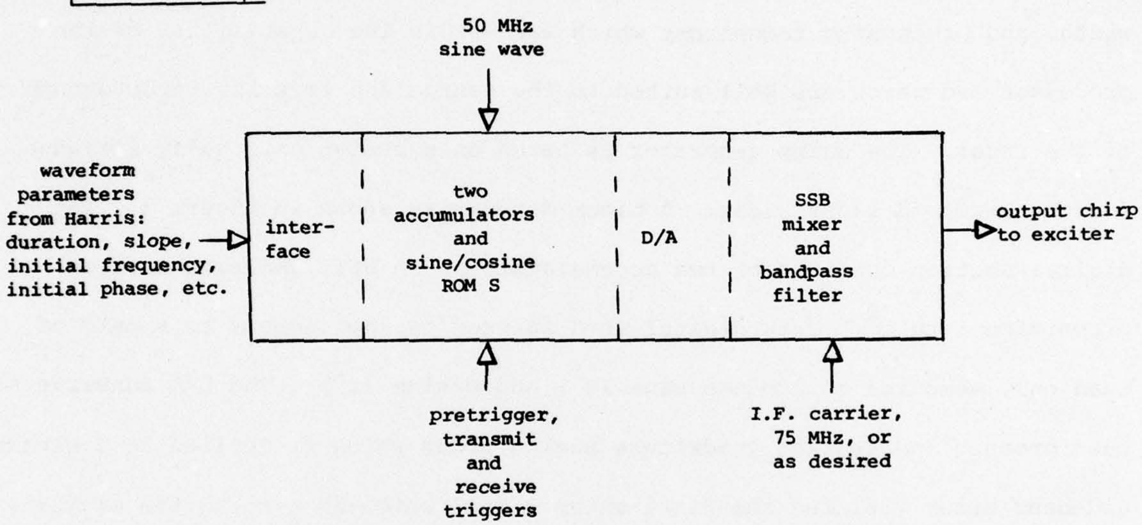

Fig. 3. Digital chirp generator.

VI. RECEIVER MODIFICATIONS

The implication of the chirp generator on the receiver is more complex. A general block diagram is shown in Fig. 4. In the CW mode, a narrowband IF, about 8 KHz, is used for reception. The chirp signals require a wider bandwidth and a 100 KHz phase compensated filter has been tentatively selected. The IF bandwidth must be selectable by the radar computer consistent with the waveform in use. In addition to waveform parameters, the Harris will supply the chirp generator with the time to the start of the receive window so that the proper timing signals can be generated and the local oscillator to the correlation mixer will start at the proper time.

Two alternatives are available for selecting the basic bandwidth for the CW search waveform. One is to select one of two IF filters under computer control. The filters are about 8 KHz and 100 KHz bandwidth, the former for the CW search waveform and the latter for the chirp waveforms. The alternate is to have a single relatively wideband IF and perform the basic narrowbanding by implementing an integrate-and-dump type of filter in the software of the digital signal processor. At present, it appears that there are sufficient CPU cycles to perform this function on the fly if desired. The compelling reason for not performing this function digitally is the sensitivity loss that would be encountered. As shown in Figure 5, it may be as much as 1.4 dB with an average value of 0.6 dB. The digital technique would be to integrate N samples and then output one sample, i.e., to undersample by a factor of N. This has the effect of building a sin x/x

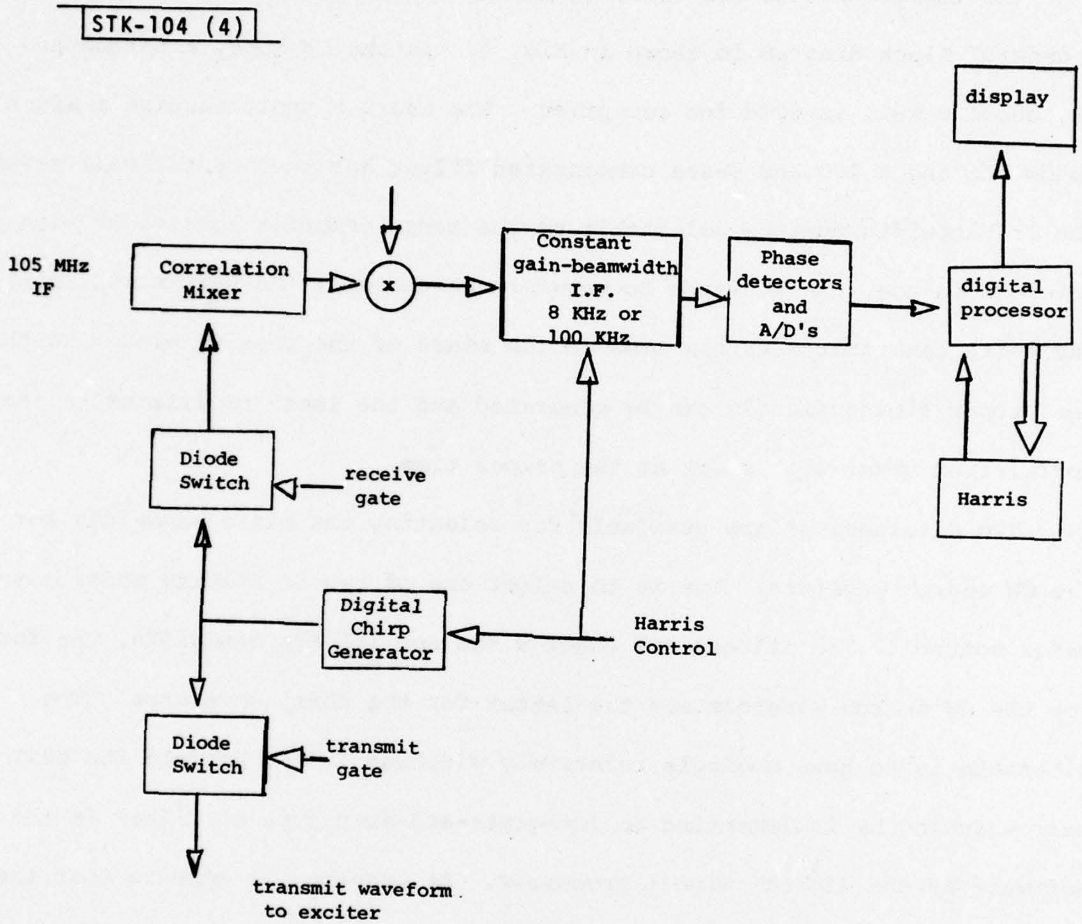

Fig. 4. Receiver modifications.

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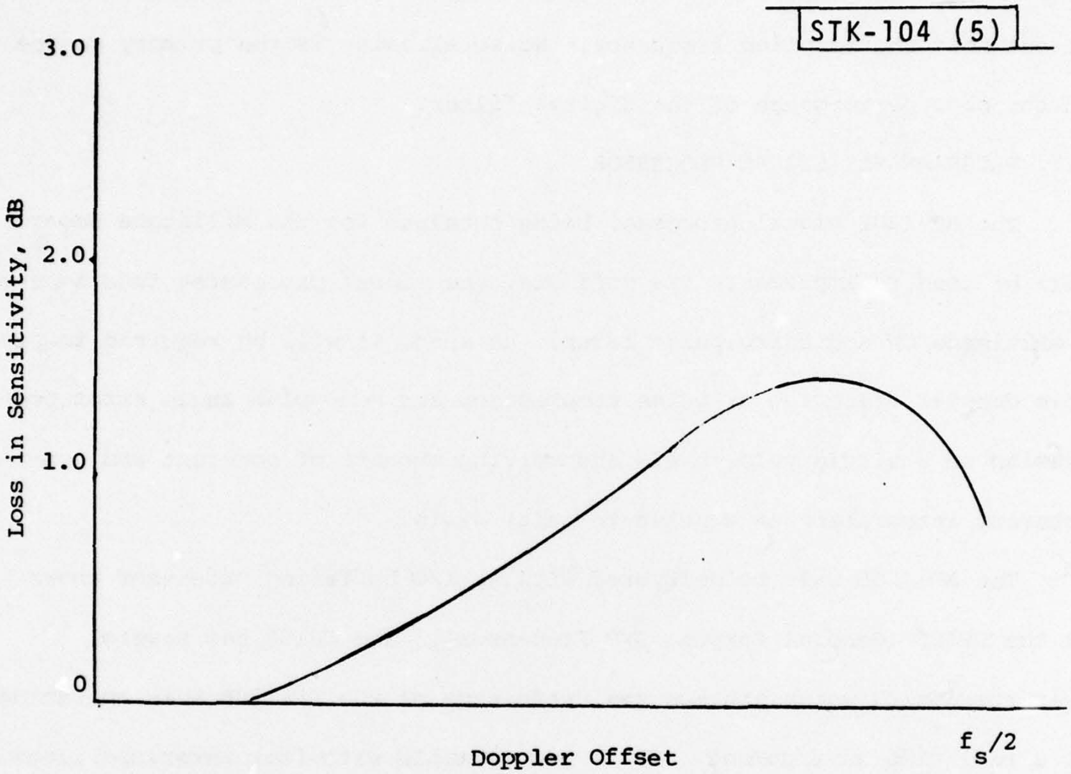

Fig. 5. Comparison of digital integrate and dump with analog I.F. filter in sensitivity.

filter in the frequency domain with the 3.9 dB point at one half the sampling frequency. The comparison is an analog filter whose amplitude shape represents that of a four pole Butterworth with the 3 dB frequency at one half the sampling frequency. Noise aliasing is the primary source of the poor performance of the digital filter.

VII. PROGRAMMABLE SIGNAL PROCESSOR

The AP-120B signal processor being obtained for the Millstone Radar will be used to implement, via software, the signal processing functions of a multimode CW and chirp pulse radar. As such, it will be required to perform doppler filtering or pulse compression and monopulse angle error processing on a single pulse basis and varying amounts of coherent and non-coherent integration on a pulse to pulse basis.

The AP-120B will be delivered with an I/O buffering processor known as the GPIOP (General Purpose I/O Processor). The GPIOP has several characteristics which enhance the usefulness of the AP-120B when operating in a real time environment. It is programmable with four interrupt lines; it contains an arithmetic unit for simple processing functions; it includes an internal FIFO (First In First Out) buffer memory which may be loaded by the external device without program interaction. An alternate DMA (Direct Memory Access) interface available with the AP-120B contains none of these features and has a lower data transfer rate limit than the GPIOP.

The basic function that the GPIOP will perform is the transfer of radar video from the output of the FIFO to the AP-120B main memory. Prior to the transfer of the radar video an interrupt should be sent to the GPIOP

on one of the interrupt lines in order to set the program counter to the subroutine that will handle the transfer of data. The maximum data transfer rate for direct transfers appears at this time to not be limited by the CPU time in the GPIOP but rather by the DMA rate to main data memory. This is advertised as 3 MHz but in fact is somewhat lower due to refresh of the dynamic MOS memory, programs executing in the AP-120B, and any AP to host data transfers which have a higher priority on the DMA line. At worst case, an isolated transfer from the GPIOP may be held off by up to 1.5 μsec but because of the low frequency of occurrence and due to the use of a FIFO buffer the actual maximum transfer rate is not expected to fall substantially. As previously described, the radar video is simply transferred to main data memory and may be either in packed or unpacked format. However, these formats will differ by a factor of two in the maximum A/D sampling rate. If the sampling rate of the A/Ds will permit, it is more convenient to use unpacked data. With the GPIOP, it is possible to float the integers from the A/Ds on the fly thereby relieving the software in the AP from this task. However, the transfer rate is now limited to 1.5 MHz and while this does not impact the decision to use this feature at Millstone, it is an unfortunate bottleneck.

Figure 6 is an outline of the executive software in the signal processor. This routine waits for the end of the data transfer from the A/D converters, initiates the intrapulse processing and if the last set of data has been received, starts the interpulse processing. It must also keep track of the idle time, i.e., the percent of real time that is not being used.

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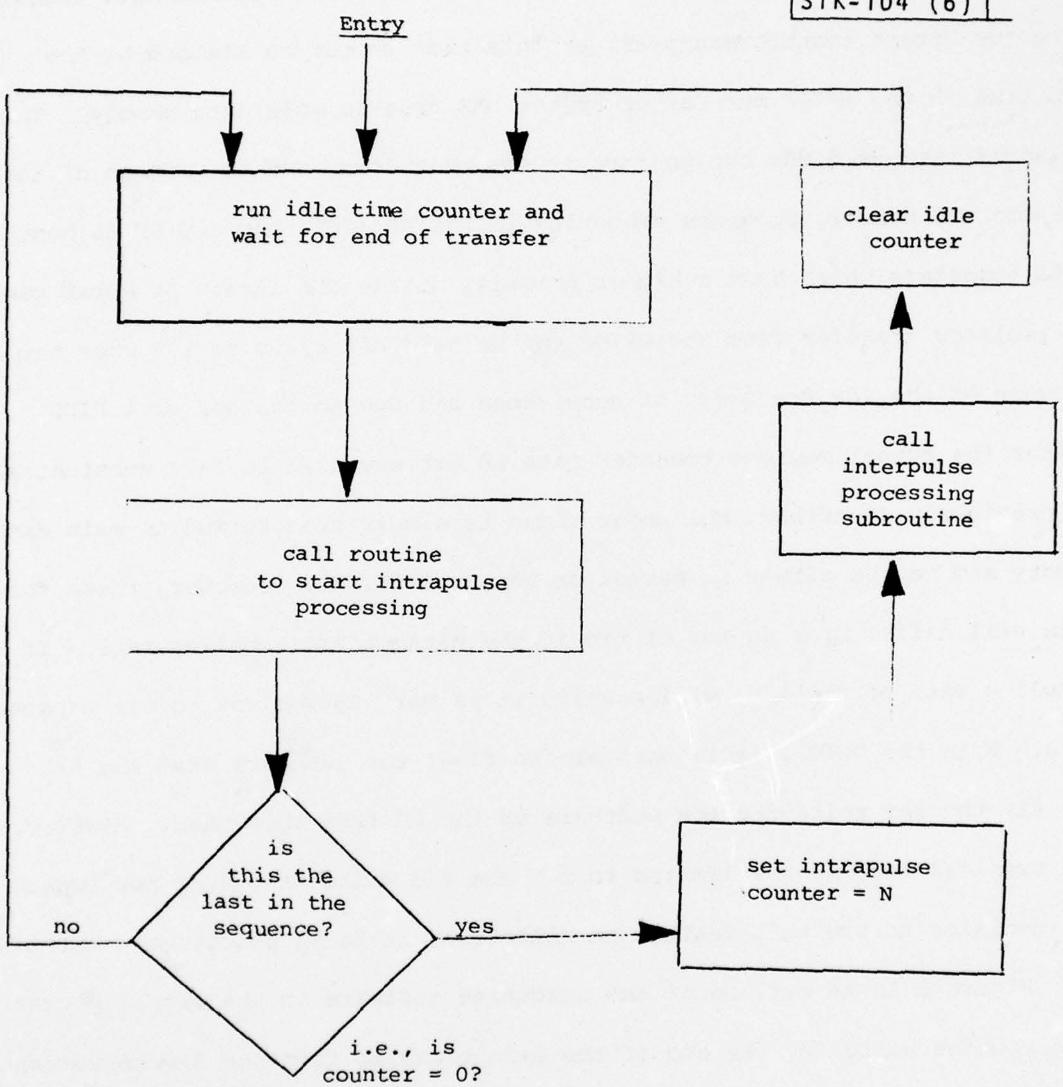

Fig. 6. Signal processor executive level software.

The intrapulse processing must be completed before the end of the next data transfer (typically 30 msec later). This is repeated until N sets of data have been received, i.e., N intrapulse processing steps have been completed. The results of this processing serve as the input to the interpulse processing. The interpulse processing runs at a lower priority than the intrapulse processing. This situation is depicted in Figure 7. In this example, four data sets are processed (intrapulse) before the interpulse processing starts. Note that the interpulse processing for block k is being interrupted by the intrapulse processing for data set k + 1. Any subroutine in the interpulse processing sequence which is executing at the time the data transfer ends may run to completion. This is an important point in the design philosophy of the software and comes about primarily because of restrictions imposed by the architecture of the signal processor. This is the fact that the AP-120B itself is not interruptible (although the GPIOP is), and the arithmetic pipelines have no hardware provisions for saving the contents of the clocking registers. This latter fault is a common characteristic of this generation of signal processors. At the end of the interpulse processing, the results are transferred to host memory by the AP and the host is interrupted.

The initiation of the intrapulse processing is accomplished by a call to the subroutine which is outlined in Figure 8. This immediately sets up the parameters for the next data transfer. It decrements the counter which is keeping track of the data sets as they arrive and receive intrapulse

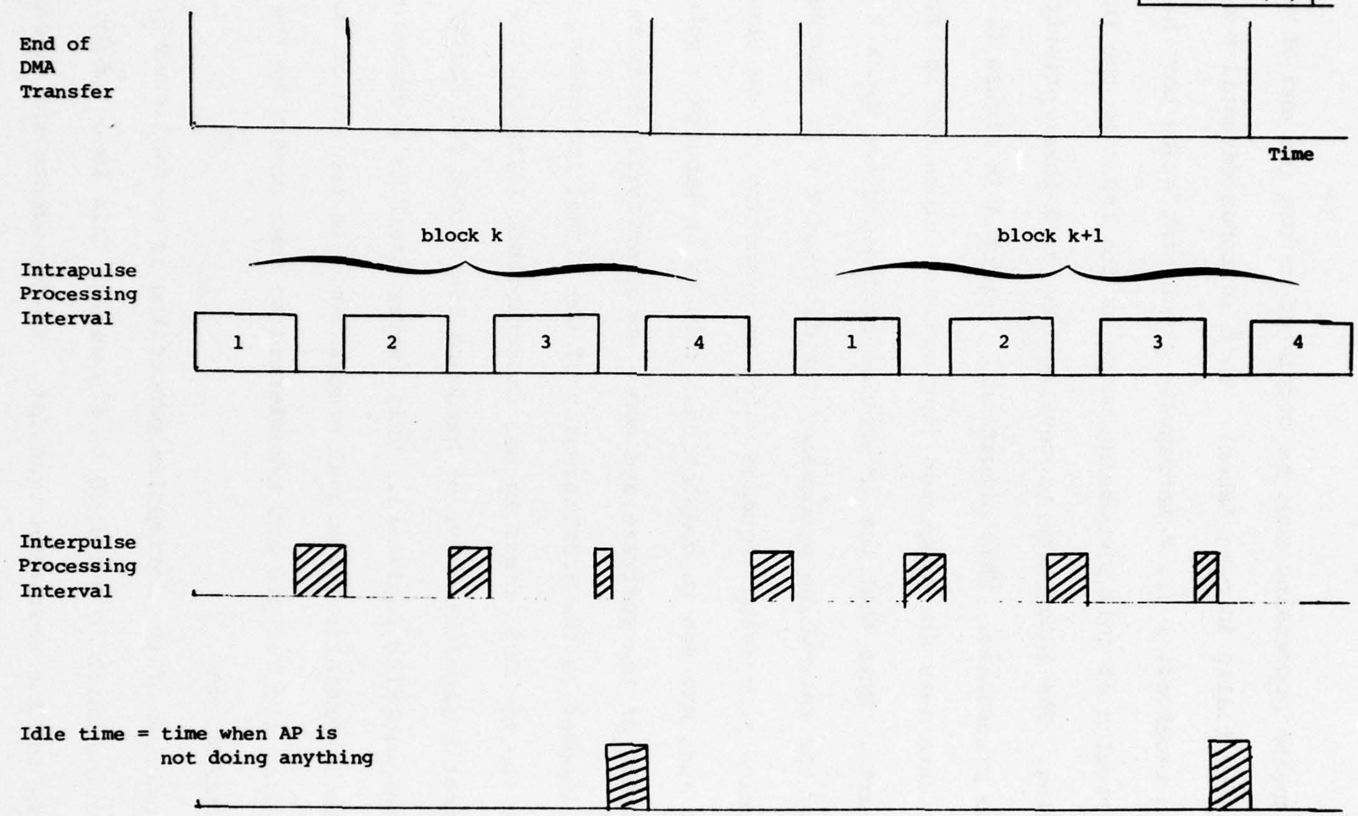

Fig. 7. Timing sequence.

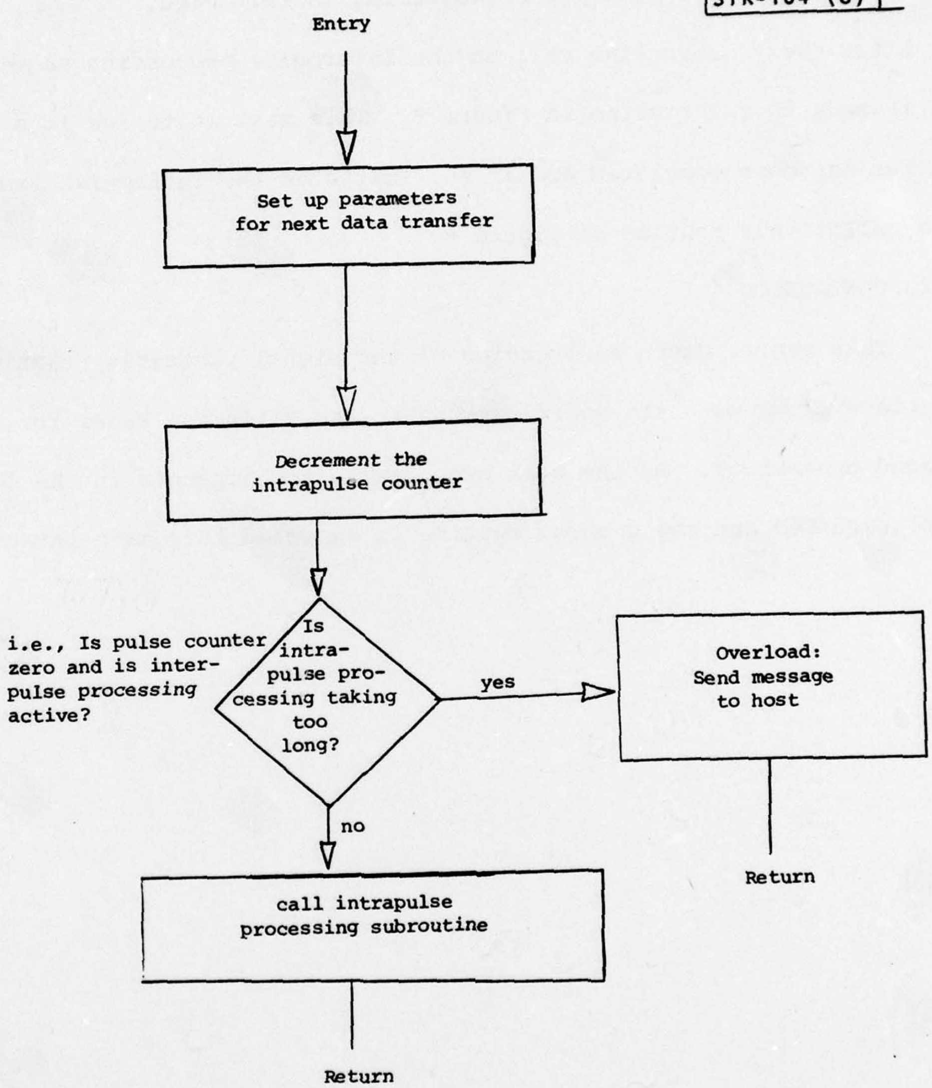

Fig. 8. Subroutine for initiating intrapulse processing.

processing. If the processing time exceeds real time, the panic button is pushed; otherwise the intrapulse processing is initiated.

After every subroutine call in the interpulse processing sequence, a call is made to the routine in Figure 9. This test is to see if a data transfer has been completed and if so, initiates the intrapulse processing via a call to the routine of Figure 8.

VIII. CONCLUSION

This report gives an overview of the signal processing that will take place along with the modifications to the Millstone Radar for its enhanced capability. As the work progresses, some changes in the details may be required but the general outline is expected to remain intact.

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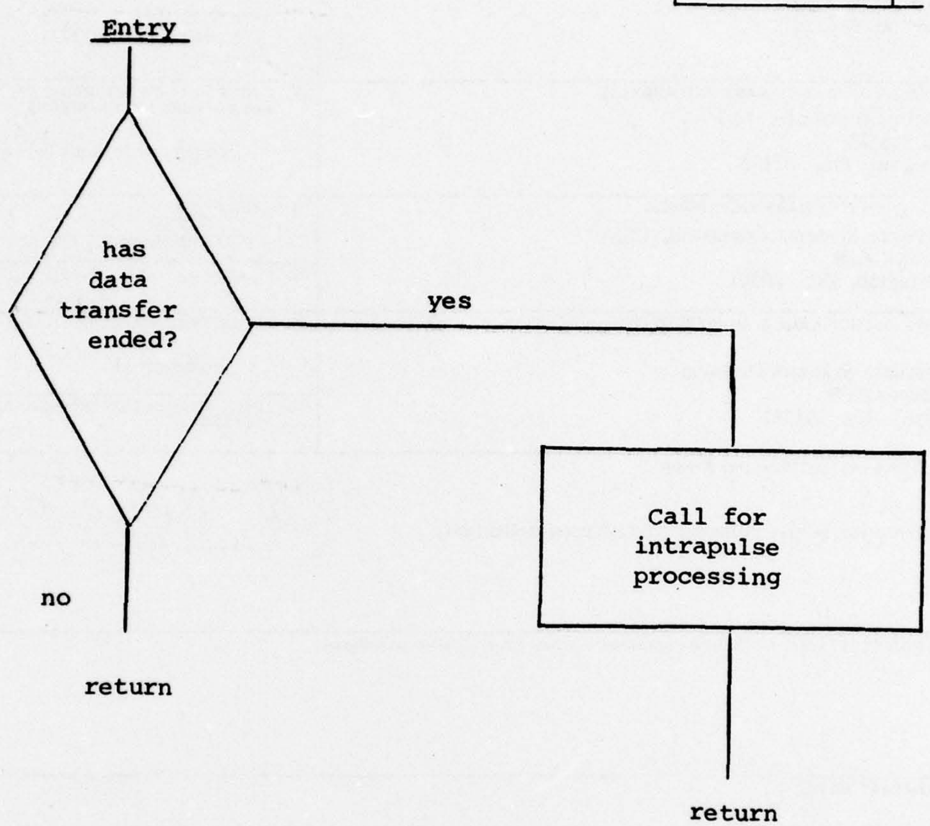

Fig. 9. This subroutine is called after every subroutine in the interpulse processing sequence.

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This report describes the new signal processing portions of the Millstone radar. Included is the waveform design for deep space search and tracking functions and the implementation and integration of these functions into the existing radar. A computer controlled digital waveform generator and a programmable array processor are the two important pieces of hardware required in the upgrade.

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